MODELING AND SIMULATION OF A SOLAR-POWERED ABSORPTION COOLING SYSTEM LOCATED IN SOUTHEAST BRAZIL

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Abstract. *The main focus of the present work is to assess the technical and economic viability of running an absorption refrigeration cycle using hot water from a solar heater and natural gas as the auxiliary energy source. The complete system (solar collectors, storage tank, and absorption cycle) was modeled and a computer routine was written to predict its performance on an hourly basis. Numerical results were obtained for a typical daily cooling load profile of two computer classrooms and actual weather data for Itajubá, Minas Gerais, southeast Brazil. It was then possible to determine the flat-plate total collector area required, hot water storage tank volume, and life cycle cost.*

Keywords*: absorption refrigeration cycle, solar heater, natural gas, cooling load, economic analysis*

1. Introduction

The environmental impact caused by the increasing demand for refrigeration is becoming a central issue for the scientific community. It has been estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air conditioning processes of various kinds (IIR, 1982). On the other hand, it has been observed that peaks in electricity demand occur more frequently during the summer period in most countries due to the use of air conditioning (Papadopoulos *et al*., 2003). Therefore, the close coincidence of the maximum insolation and the peak cooling load indicates the possibility of using solar energy as the main heat input in air conditioning systems. This is even more so in tropical climates where there is an abundant supply of solar energy. Besides contributing to the reduction in the electricity demand, solar assisted refrigeration results in decreased CO_2 emissions and the elimination of CFCs and HCFCs.

In this context, absorption refrigeration systems have been the object of several studies. The most common absorption systems are the $LiBr/H_2O$ and H_2O/NH_3 ones, which are used in distinct application due to the different evaporation temperatures attained. Because water is used as the refrigerant, $LiBr/H_2O$ systems are limited to applications that do not require very low evaporation temperatures, e.g., comfort air conditioning. In contrast, H_2O/NH_3 systems are used for food refrigeration, ice making, and similar applications because ammonia is the refrigerant and very low evaporation temperatures are possible. The $LiBr/H_2O$ systems operate satisfactorily at a generator temperature of 88 ^oC to 93 ^oC, achievable by a flat plate solar collector, and exhibit a larger COP than H_2O/NH_3 systems (Kreider and Kreith, 1982). In practice, the evaporator cannot operate at temperatures much below 4.5 ^oC, which are nonetheless within the range suitable for comfort air conditioning.

The major problems facing solar absorption cooling systems are its high initial cost, low system performance, and the relative low heat transfer rates that can be derived from solar radiation for operation over shorts periods (Li and Sumathy, 2001). The coefficient of performance of $LiBr/H_2O$ systems usually decreases substantially when operated by heat sources at temperatures below 85 ^oC (Atmaca and Yigit, 2003; Ghaddar *et al*., 1997). Under conditions of sufficient insolation (5.5 kWh/m^2.day) most solar refrigeration systems have overall efficiencies in the 8% to 11% range (Best and Pilatowsky, 1998). In a scenario where electricity costs are still fairly low, the cost of solar absorption systems will have to be reduced by a factor of three to five in order to make them competitive with conventional vapor compressor systems. Therefore, the optimization of the solar collector area and operating temperatures is among the first requirements for setting up limits within which solar absorption systems could become economically attractive (Colle and Vidal, 2004). Increasing costs of electricity worldwide in recent years associated with decreasing production costs of solar collectors in many countries are contributing to broadening these limits.

The main focus of the present work is to assess the technical and economic feasibility of operating an absorption refrigeration cycle using hot water from a solar heater and natural gas as the auxiliary energy input. This choice is based on the fact that natural gas is likely to become one of the major energy sources in Brazil in the coming years.

The complete system modeled is composed by a $LiBr/H_2O$, single stage absorption cycle with a 10 TR nominal refrigeration capacity, solar collectors, and storage tank. Performance predictions were obtained on an hourly basis using typical daily cooling load profiles of two computer classrooms and actual weather data for Itajubá, Minas Gerais, southeast Brazil. The economic analysis was performed using the *LCC* and the P_1, P_2 methods presented by Duffie and Beckman (1991). The P_1, P_2 method allows for the determination of the optimal collector area for a given cooling load and storage tank volume. This optimum is defined as the area that maximizes the Life Cycle Savings (*LCS*), the difference between the total costs of a fuel-only system and a combined solar/fuel system.

2. The use of natural gas in Brazil

Natural gas is produced in over 70 countries and its commercial distribution is not controlled by the Organization of the Petroleum Exporting Countries (OPEC); consequently, its price tends to be less affected by monopoly influences. In fact, prices have decreased substantially worldwide to the present 7 to 11 U$/oeb (oil equivalent barrel). On an energy basis, production costs for natural gas are lower than those for charcoal and oil by a factor of 6.6 and 2.6, respectively. To this end contributes a more uniform distribution of gas reserves around the world. In addition, as natural gas cannot be easily transported over long distances, approximately 90% of the world consumption is produced locally or in nearby countries.

In Brazil, the main natural gas reserves are located in the Campos basin, Rio de Janeiro State. According to the Brazilian Energy and Mines Department (MME, 1995), all the reserves already measured and accounted for total about 25% of the oil reserves or 146.5 x 10^9 m^3; estimated reserves are 86.9 x 10^9 m^3. New reserves have been found recently, which could substantially increase these numbers. In Juruá, Amazonas State, preliminary estimates have pointed to gas reserves in the 120 to 200 x 10^9 m^3 range; about 10^9 m^3 have already been confirmed. However, it would be necessary a 3,000 km pipeline at a cost of U$5 billions for this gas to be transported to the southeast, where demand is high.

The percentage contribution of natural gas to the total national energy consumption has increased significantly in recent years, from 0.3% in 1973 to 2.5% in 1994 (MME, 1995). In the year 2000 this percentage was 4% and it is expected that in 2020 it will rise to 15% as long as the supply can be assured (Duarte *et al*., 1995). This increased demand could be met by gas import from Bolivia and Argentina and by measures to enforce gas production from oil reserves where it is currently flared out. The use of natural gas in Brazil is expected to grow as the governmental policies on air pollution become stricter. It will probably be more widely used in motor vehicles, cogeneration systems, and thermoelectric plants along the Brazil/Bolivia pipeline, especially in Southern Mato Grosso State.

Like any other non-renewable energy source, natural gas reserves will eventually be used up. Brazilian reserves are expected to last 28.4 years at the present consumption rate; increased consumption will obviously reduce this time period. In ten to 15 years the demand for gas will surpass the supply, with a potential risk for an energy crisis and drastic prices increase (Pinheiro, 1996). Today's prices for the commercial sector are about R$1.65/$m^3$, tax included (COMGAS, 2005). Recent political unrest in Bolivia is also likely to have an impact on current prices.

3. System description and modeling

The system modeled in the present work is shown schematically in Fig. 1. Solar energy is absorbed in the collectors and accumulated in the hot water storage tank. Hot water is then made to flow through the absorption system generator to boil off water vapor from the LiBr/H_2O solution. Natural gas is used as the auxiliary heat source when insolation is not enough to heat the water in the storage tank to the temperature level required by the generator. The high pressure water vapor boiled off in the generator is turned liquid in the condenser and forced to flow through an expansion valve into the evaporator. There, the low pressure liquid evaporates providing the cooling effect. Meanwhile, the strong hot LiBr/H_2O solution leaving the generator to the absorber passes through a heat exchanger in order to preheat the cold weak solution returning to the generator. Water from the cooling tower removes heat from the absorber and condenser, thereby keeping appropriate temperatures in these components. Chilled water from the evaporator flows through the fan-coil to absorb the cooling load.

This system is being built at the Laboratory for the Study of Thermal Systems of Federal University of Itajubá (NEST-UNIFEI); the chiller used is a Thermax/Cogenie model, single stage, 10TR nominal refrigeration capacity, 0.70 coefficient of performance, requiring a 7.8 m^3/hr hot water supply in the 85 to 90.6 ^oC temperature range. The conditioned space simulated is made of two computer classrooms located in Itajubá, MG, southeast Brazil. In calculating the monthly cooling loads (Tab. 1), actual weather data collected by the Brazilian National Space Research Institute (INPE) for Itajubá were used.

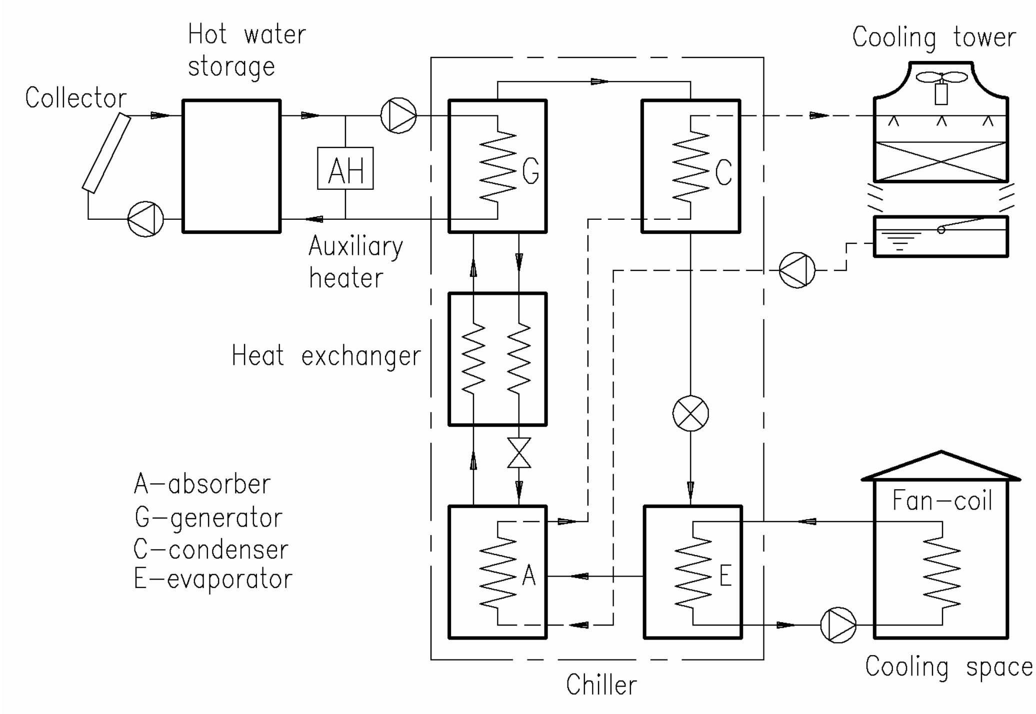

Figure 1. Schematics of system modeled.

Table 1. Monthly weather data for Itajubá (MG), cooling loads (Q_e) for two computer classrooms, and total heat input in the absorption cycle generator (Q_g).

Month	T_a [°C]	H [MJ/m^2.day]	Q_e [GJ]	Q_g [GJ]
Jan	22.4	18.90	32.34	49.76
Feb	22.2	19.19	28.08	43.20
Mar	21.5	18.18	30.27	46.57
Apr	20.0	18.53	22.31	34.33
May	16.2	14.83	23.40	35.99
Jun	13.1	13.77	18.33	28.20
Jul	15.2	14.20	19.60	30.15
Aug	16.8	16.43	19.19	29.53
Sept	18.7	17.59	20.48	31.51
Oct	20.8	19.76	26.63	40.97
Nov	21.1	19.55	23.35	35.93
Dec	22.2	19.28	28.61	44.02

The solar collectors and hot water storage tank were modeled following the formulation presented by Duffie and Beckman (1991). It follows that,

$$Q_u = A_c I \eta_c \tag{1}$$

where Q_u is the useful heat transferred to the water in the storage tank, A_c is the collector area, I is the hourly solar irradiation, and η_c is the collector efficiency given by:

$$\eta_c = F_R(\tau\alpha) - F_R U_L\left(\frac{T_{in} - T_a}{I}\right) \tag{2}$$

where T_{in} is the collector inlet water temperature, T_a is the ambient temperature, and F_RU_L and $F_R(\tau\alpha)$ are parameters characteristic of the solar collectors (Duffie and Beckman, 1991).

For the flat-plate collectors simulated, F_RU_L = 6.253 W/m^2.^{o}C and $F_R(\tau\alpha)$ = 0.708 (INMETRO, 2001). Assuming there is no stratification and the heat transfer rate to and from the storage tank to remain essentially constant over an appropriate time interval, Δt, the mean water temperature in the tank at the end of each time interval can be calculated from

$$T_{s,new} = T_{s,old} + \frac{\Delta t}{(M\, c_p)_s}\left[Q_u - Q_L - (UA)_s\left(T_{s,old} - T_{as}\right)\right] \tag{3}$$

In this equation, Q_L is the energy extracted from the storage tank, M is the water mass in it, $(UA)_s$ is the tank overall heat transfer coefficient, and T_{as} is the ambient temperature where the tank is located.

In case the water temperature is below that required by the chiller generator, auxiliary heat input from natural gas is necessary. The ratio of the energy extracted from the storage tank, Q_L, to the total energy needed in the generator, Q_g, is called solar fraction, given by,

$$f = \frac{Q_L}{Q_g} \tag{4}$$

The relationship between the hot water storage tank volume and the collector area varies widely in the literature (Ghaddar *et al*., 1997; Li and Sumathy, 2000; Atmaca and Yigit, 2003; Lozano, 2004; Syed *et al.*, 2005) from 13 to 200 liters/m^2. In general, smaller systems admit lower values of the V_s/A_c ratio whereas larger systems usually require higher values. This is due to the fact that larger systems demand higher heat transfer rates in the generator, which cannot be obtained from a near-steady-state energy transfer from the solar collectors. Anyway, whatever the Vs/Ac ratio adopted, the bottom-line is that the water in the tank should not boil (Joudi and Ghafour, 2003).

From these equations one can obtain, for each month of the year, typical hourly profiles of the mean water temperature in the tank, the useful energy transfer to the stored water, the energy extracted from the tank, the auxiliary energy input, and the corresponding solar fraction. These profiles, in turn, allow for the yearly total energy input required by the solar system and the auxiliary fuel consumption. Once these results are introduced in the economic analysis equations, one can determine the optimal collector area for a given storage tank volume. The performance and the economic analysis equations were programmed into a Microsoft Excel spreadsheet so that different values of the design parameters (collector area and storage tank volume) could be tested. In addition, simulations for different values of fuel and solar equipment costs were also made.

4. Economic analysis

There are two basic methods to compare the costs of any two or more solar systems (Elsafty and Al-Daini, 2002). The first one is called First Cost Comparison. It takes into account only the initial investment required to get the system installed and ready to operate; this method ignores important factors such as expected life, ease of maintenance, and, to some extent, even efficiency. Typically, the first cost comparison is used in buildings built for speculation or short-tem investment. The second method is the Life Cycle Cost (*LCC*), which includes all cost factors (initial cost, operating cost, maintenance, replacement, and estimated energy use) and can be used to evaluate the system total cost over its entire lifetime. The basic idea of the *LCC* method is that anticipated future costs are brought back to present cost (discounted) by calculating how much would have to be invested at a market discount rate (the rate of return on the best alternative investment) to have the funds available when they will be needed. An *LCC* analysis includes inflation when estimating future expenses (Duffie and Beckman, 1991).

In this work, the *LCC* method is used to assess the economic feasibility of three refrigeration systems, namely, an absorption refrigeration system using solely natural gas for the heat input (System I), an absorption system using both natural gas and solar energy (System II), and an electricity-driven vapor compression system (System III). The system that exhibits the lowest *LCC* value is the most feasible one from the economic standpoint. In order to determine the optimal collector area for system II, a Life Cycle Savings (*LCS*) analysis was carried out. Life Cycle Savings (net present worth) is defined as the difference between the life cycle costs of a conventional fuel-only system and the life cycle cost of the solar plus auxiliary energy system (Duffie and Beckman, 1991). Calculation of the *LCS* value can be made by means of the P_1, P_2 method (Duffie and Beckman, 1991) in which cost factors are combined into a simple formulation,

$$LCS = P_1 C_{F1} L f - P_2 C_S \tag{5}$$

In this equation, P_1 is the ratio of the life cycle fuel cost savings to the first year fuel cost savings; P_2 is the ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment; C_{F1} is the first period's unit energy cost delivered from fuel ($/GJ); L is the system's energy consumption during the first year (GJ); f is the solar fraction; and C_S is the total cost of installed solar energy equipment ($).

In calculating *LCS*, the cost of the solar collectors was assumed to be R$226.70/m^2, the cost of the storage tank was taken as R$3.90/liter, and the cost of natural gas was taken as R$1.65/m^3 (tax included), which corresponds to R$46.64/GJ. The annual thermal energy demand (total heat input in the absorption cycle generator) is 450.16 GJ (Tab. 1).

These values were introduced in the equations above in order to obtain the collector area that allowed for the maximum *LCS* value for several sizes of the hot water storage tank (Fig. 2). It can be observed that smaller sizes allow for higher *LCS* optimal values at the expenses of increased sensitivity to variations in the collector area. Larger tank sizes make the system more "robust" from an economic point of view, but decrease the optimal *LCS* value. The 4000 liters tank size was chosen as a trade-off between these opposing trends. In this case, the maximum *LCS* is already positive and there are no fluctuations; the optimal *LCS* value was R$ 6,275.01 and the corresponding collector area and solar fraction were 230 m^2 and 0.290, respectively.

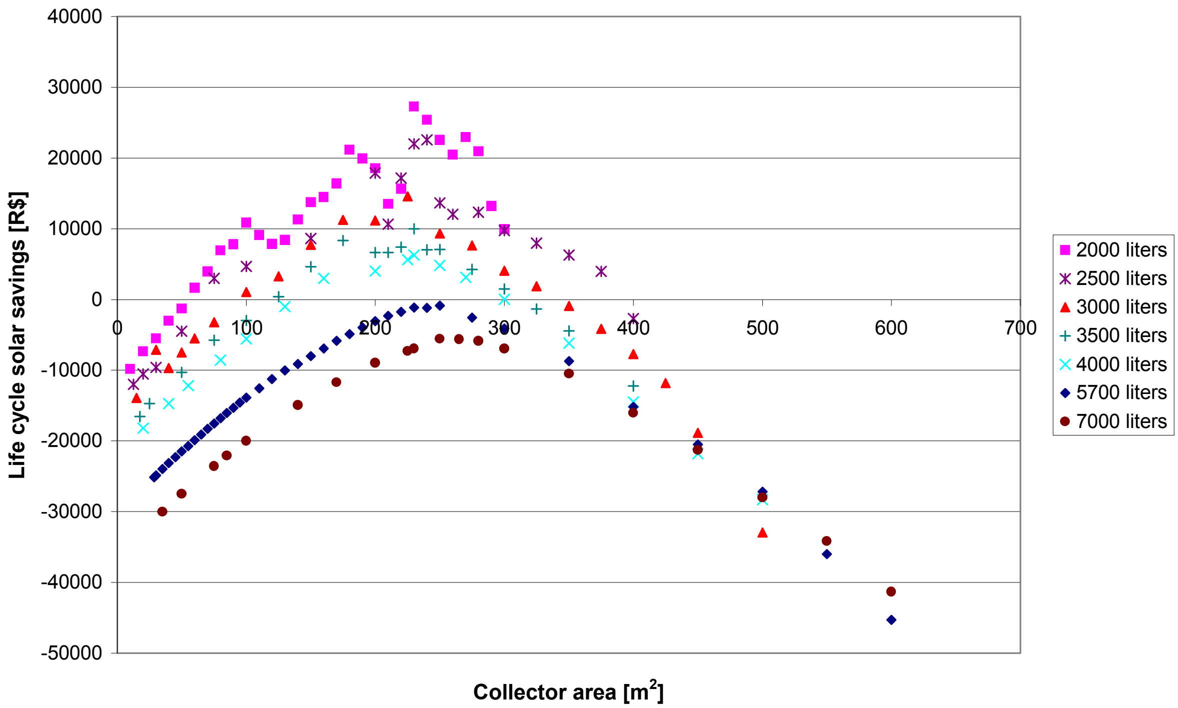

Figure 2. LCS values as a function of collector area for several storage tank sizes.

In order to compare the three systems considered, their total cost throughout their lifetime should be brought back to present. The present worth of any system equals the sum of the initial cost, *IC*, and the present worth of operating, *PWO*, and maintenance, *PWM*, costs. In mathematical terms,

$$LCC = IC + PWO + PWM \tag{6}$$

where,

$$PWO = op\sum_{j=1}^{N}\frac{(1+i)^{j-1}}{(1+d)^{j}} \tag{7}$$

$$PWM = m\sum_{j=1}^{N}\frac{(1+i)^{j-1}}{(1+d)^{j}} \tag{8}$$

In these equations, *op* and *m* are the annual operating and maintenance costs, respectively.

The system initial costs comprise the cost of the equipment itself, the cost of subsystems such as pumps and piping, and installation costs. Operating costs are those directly related to the system effective operation; among these are utilities costs such as electricity, fuel, and water. Precise maintenance costs are difficult to come by because they depend on many variables such as the system complexity, working hours, and age. From maintenance costs reported in a number of studies, Elsafty and Al-Daini (2002) concluded that the ratio of maintenance costs of absorption systems to those of compression systems lies in the 0.60 to 1.25 range. Table 2 shows the initial, operating, and maintenance costs of the three systems investigated in this work; the expected system lifetime is also shown. The electricity cost for System III was taken as R$0.57/kWh; its coefficient of performance was assumed to be 3.8 and its annual electricity demand to make up for the cooling loads shown in Tab. 1. was calculated to be 21,390 kWh. Maintenance costs for all three systems were considered to be R$150/TR per year.

It can be observed in Tab. 3 that the vapor compression system (System III) is approximately 44% cheaper than the absorption fuel-only system (System I), and 41% cheaper than the solar/fuel absorption system (System II). System II, in turn, is approximately 5% cheaper than System I. Thus it can be concluded that in the present scenario where electricity costs are still relatively low absorption systems, either fuel-only or solar/fuel powered, are not competitive. Furthermore, in view of expected prices of electricity and natural gas in the coming years, vapor compression systems are likely to remain the preferred choice of equipment of air-conditioning systems designers. A simple exercise with the routine developed revealed that for System II to become competitive with System I it is necessary not only a reduction in the costs of solar equipment and natural gas, but also an increase in electricity costs.

Table 2. Initial, operating, and maintenance costs for the three systems simulated.

	System I	System II	System III
Initial Cost	R$ 93,410.00	R$ 161,462.72	R$ 36,855.00
Annual Operating Costs	R$ 20,994.81	R$ 14,900,03	R$ 12,192.30
Annual Maintenance Costs	R$ 1,500.00	R$ 1,500.00	R$ 1,500.00
Useful Lifetime	15 years	15 years	15 years

Table 3. Present worth costs for the three systems investigated.

	IC [R$]	PWO [R$]	PWM [R$]	LCC [R$]
System I	93,410.00	301,236.65	21,522.22	416,168.87
System II	161,462.72	213,787.84	21,522.22	396,772.78
System III	36,855.00	174,936.93	21,522.22	233,314.15

5. Conclusions

The present work has shown that absorption systems, either fuel-only or solar/fuel powered, are not competitive with vapor compression systems given today's prices of electricity, natural gas, and solar equipment. However, this scenario could change as prices of electricity and natural gas go up and production costs of solar equipment are cut down.

In a future work, the authors will investigate the technical and economic feasibility of using a gas turbine / absorption cycle cogeneration system to both produce electricity for and meet the cooling load of a commercial application. It is hoped that this system will be more competitive than the stand-alone absorption systems studied in this work.

6. Acknowledgements

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